Toward Waste Heat Recovery Using Nanostructured Thermoelectrics

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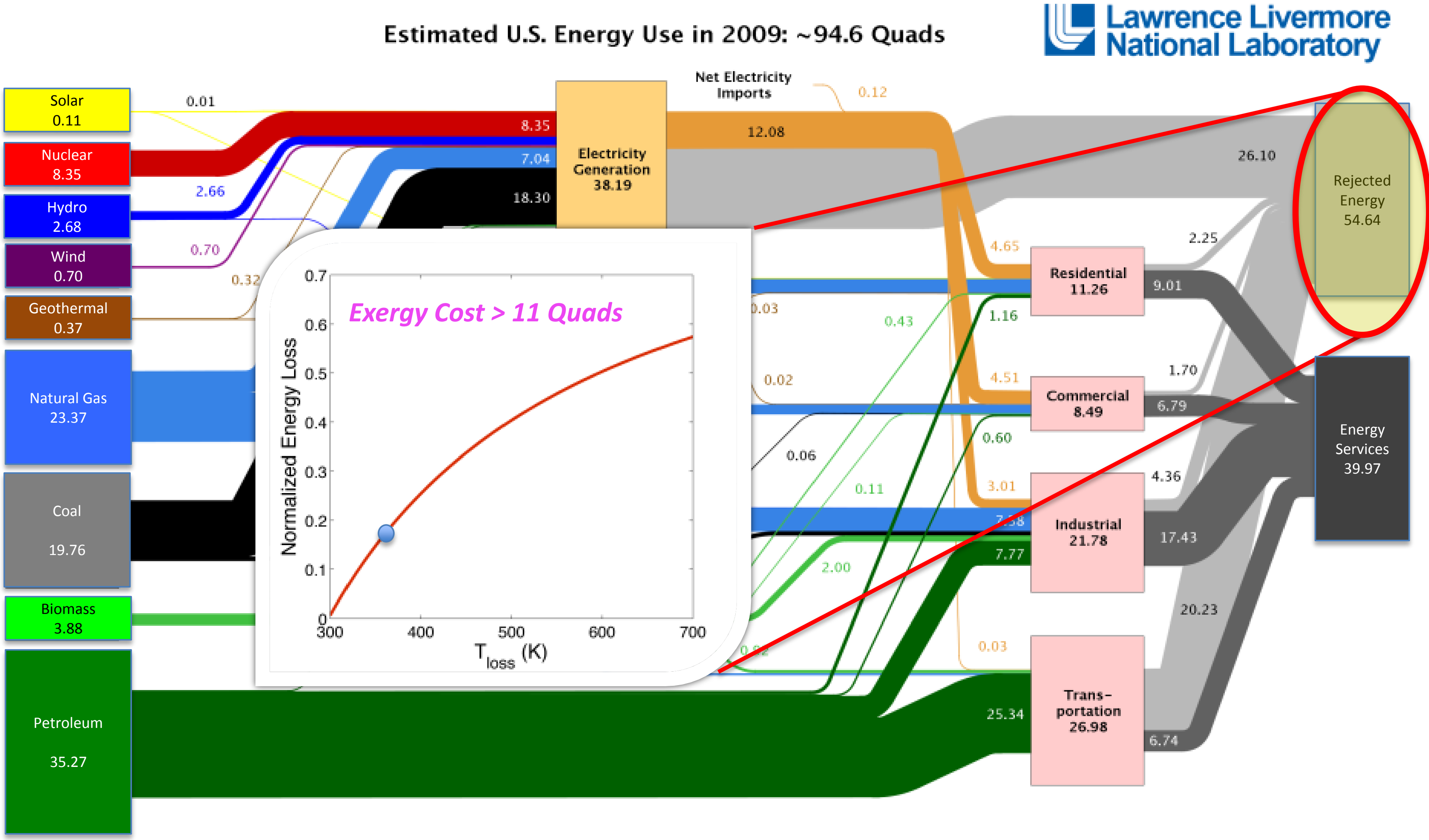
Potential for Waste Heat Harvesting

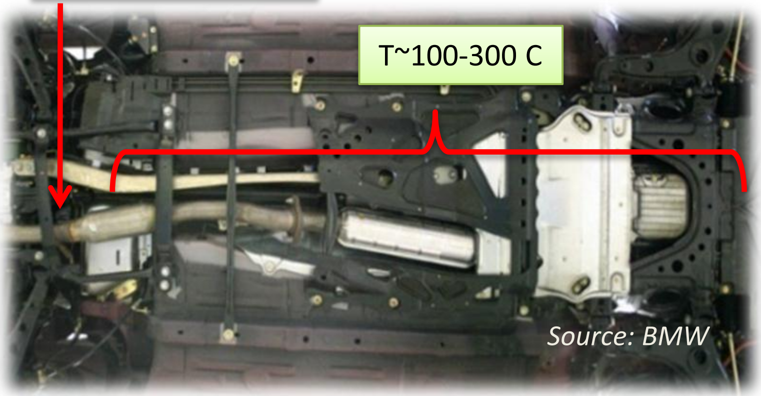


~ 57% of energy consumed in the US rejected as heat

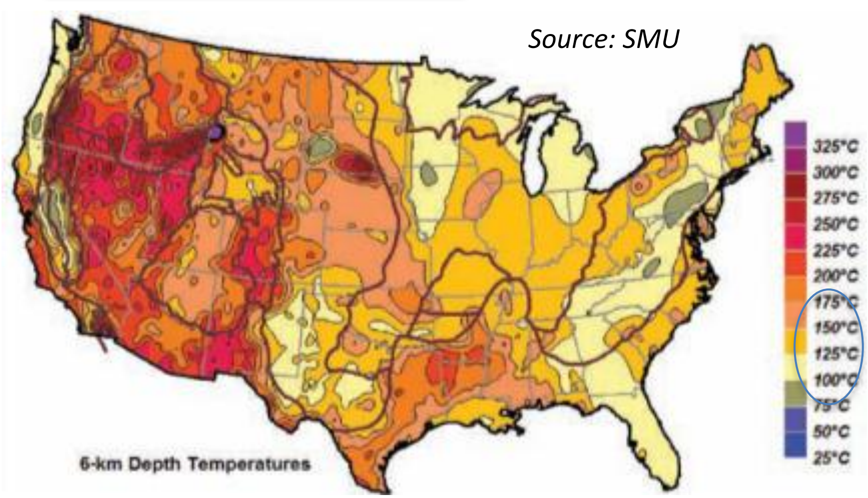
Sources of Low Quality Waste Heat

T_{water} ~ 33 C
T_{flue} ≥ 100 C ($\eta_{furnace}$ ~ 90%)

$T_{exhaust}$ ~ 400-600 C



T_{IN} ~ 27 C (ASHRAE)
δT ~ 50 – 120 C (HD, State of art at Intel)



- η_{CARNOT} (T_H=100C) ~ 20%
- Difficult to extract work
- Fluid machines infeasible
- Transcritical CO_2, organic Rankine, Kalina are expensive
- Thermoelectrics?

Thermoelectrics

Thomas Johann Seebeck (1770-1831)

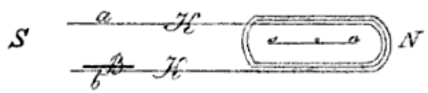


Fig. 1.

1821-22

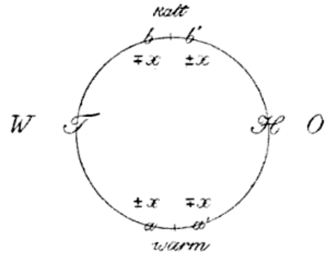


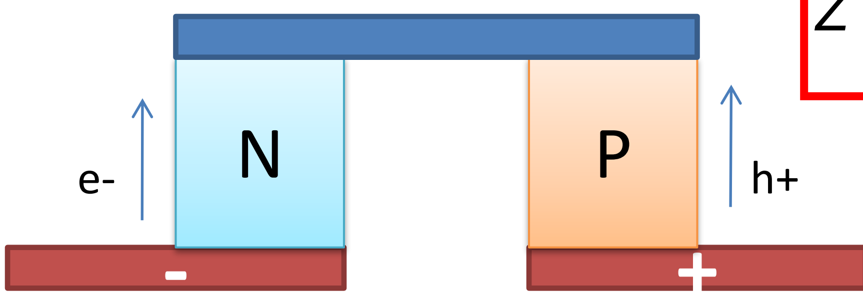
Fig. 26.

Seebeck, T.J., “Magnetische polarisation der metalle und erze durch temperaturdifferenz”, Verlag von Willhelm Engelmann, Leipzig, Germany (1895)

$$V_{SEEBECK} = \int_C^H \nabla\phi \, d\vec{r} = -\int_C^H S(T)\nabla T \, d\vec{r} = -S\Delta T$$

$$S \sim k/e \approx 10^{-4}\ V/K$$

$$Z = \frac{S^2\sigma}{k}$$



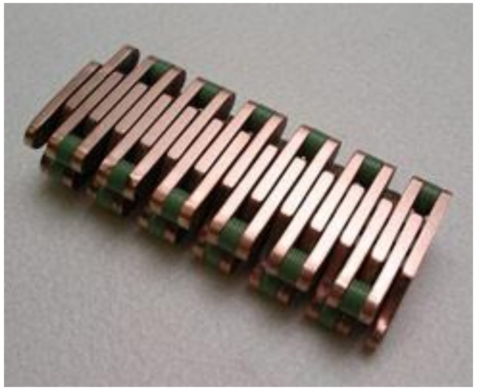
π-leg *p-n* Thermoelectric Junction

Thermoelectric Generators

- ~1820-50 **Thermopile (Nobili & Melloni)**
- 1879 **~ 200 W maximum power**
- 1905 **Patent (Yamamoto)**
- 1929 **5% efficiency, ZT (Abraham Ioffe)**
- ~1950 **kW (Russia)**
- 1960 **Bi-Sb-Te-Se alloys**
- 1977- **Radioscope TEG (Pioneer, Voyager, Galileo, Cassini …)**

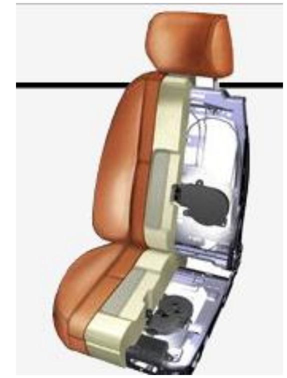
Thermoelectrics Applications

BSST

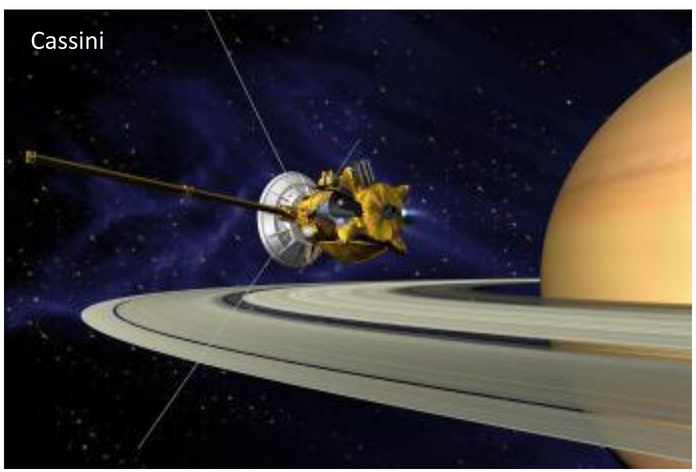


Refrigeration

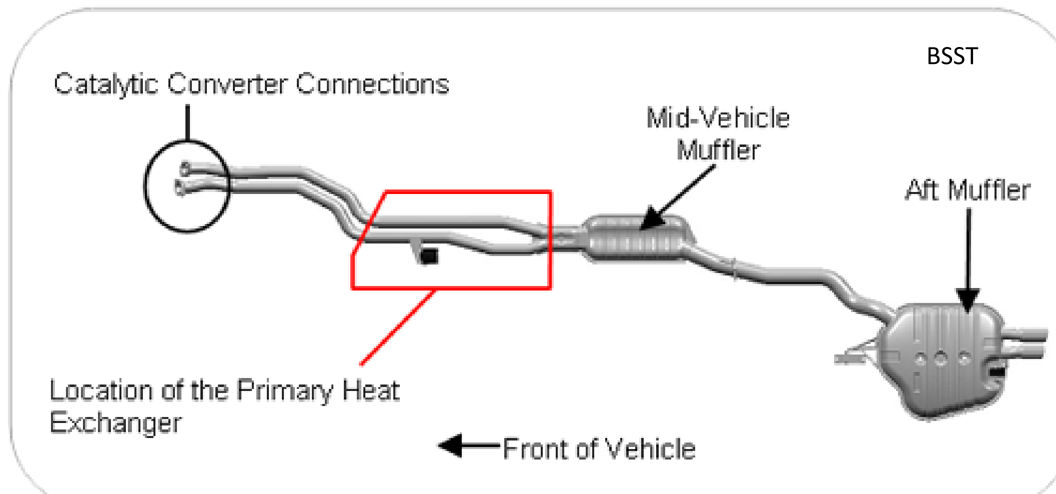
Amerigon



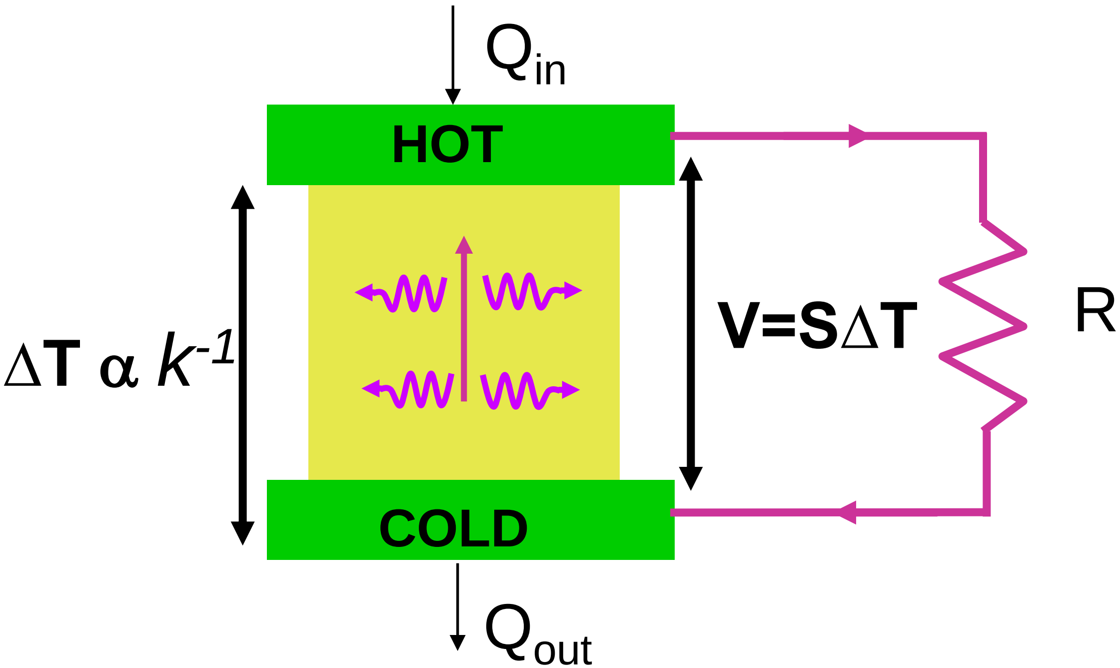
Power Generation

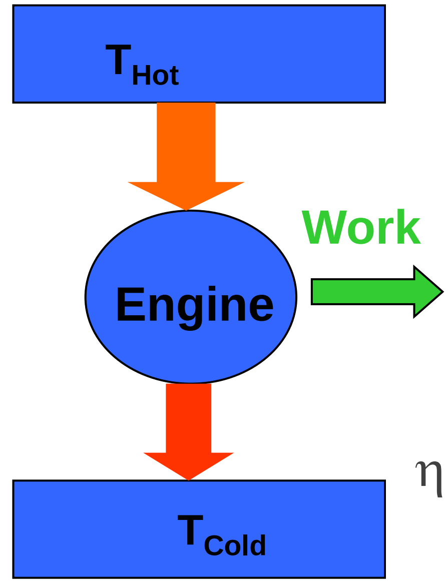


Waste Heat Recovery



The Thermoelectric Heat Engine

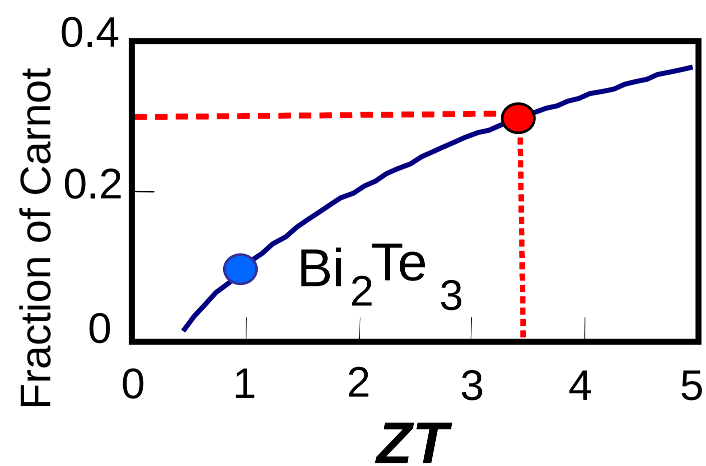




$$\eta = 1 - \frac{T_{cold}}{T_{hot}}$$

$$\eta = \eta_{CARNOT} \times \left(\frac{\sqrt{1+Z\bar{T}} - 1}{\sqrt{1+Z\bar{T}} + \frac{T_C}{T_H}} \right)$$

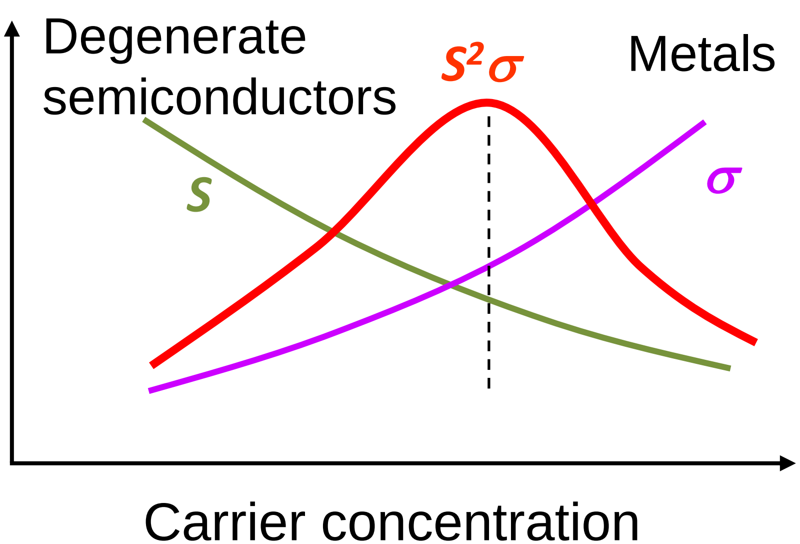
$$ZT = \frac{S^2 \sigma T}{k}$$

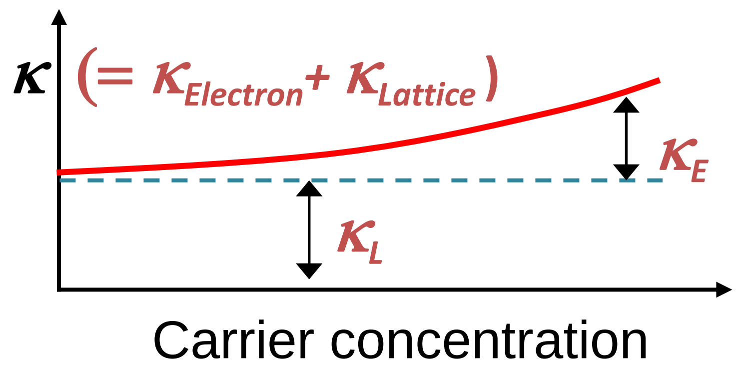


The Z Conundrum

$$Z = \frac{S^2 s}{k}$$

- Microscopic linkage between S, σ and k





$$\frac{k}{s} = LT$$

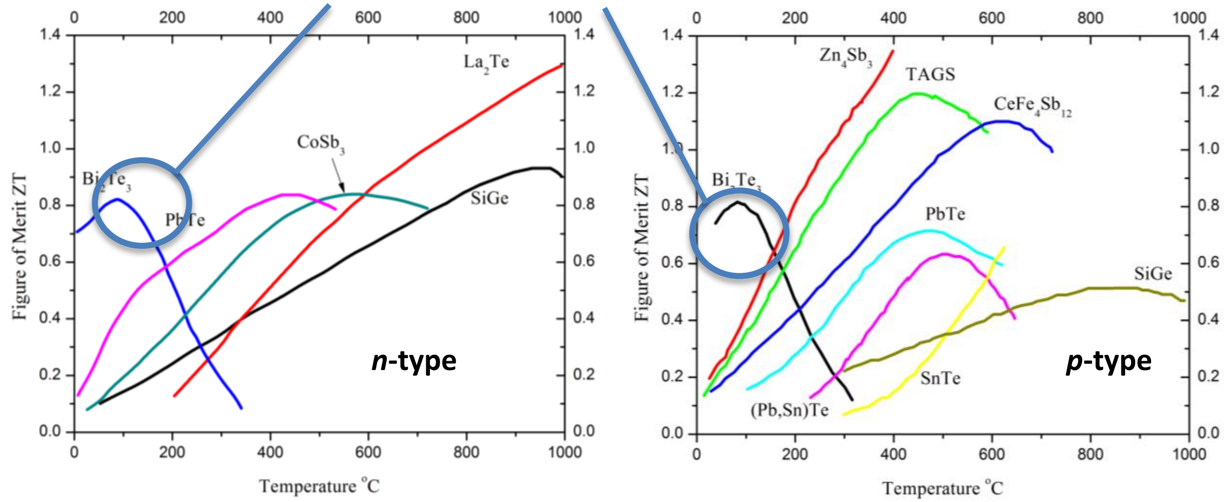
Wiedemann Franz Law

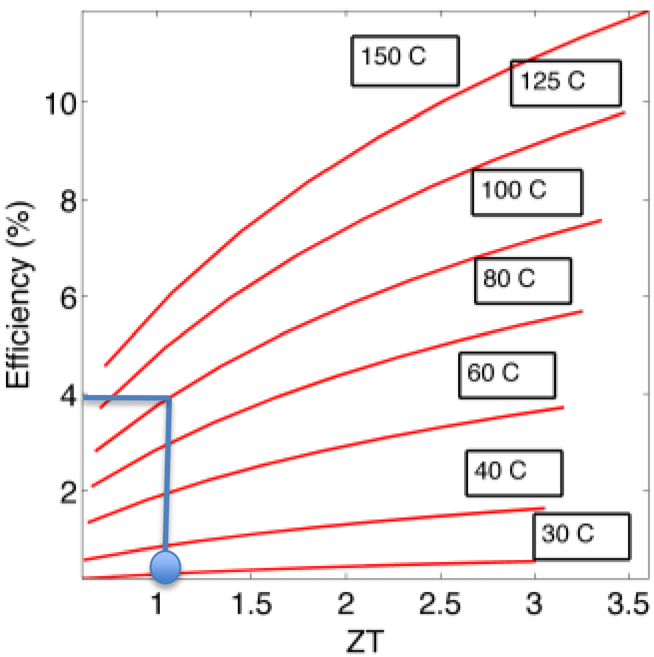
κ ⟷ σ ⟷ S

Conversion Efficiency

$$\eta = \eta_{CARNOT} \times \left(\frac{\sqrt{1+Z\overline{T}} - 1}{\sqrt{1+Z\overline{T}} + \frac{T_C}{T_H}} \right)$$

Bi_2Te_3 alloys have ZT ~ 1 at 300 K





Scalability Issues:

- Low abundance
- ~15x expensive as Si

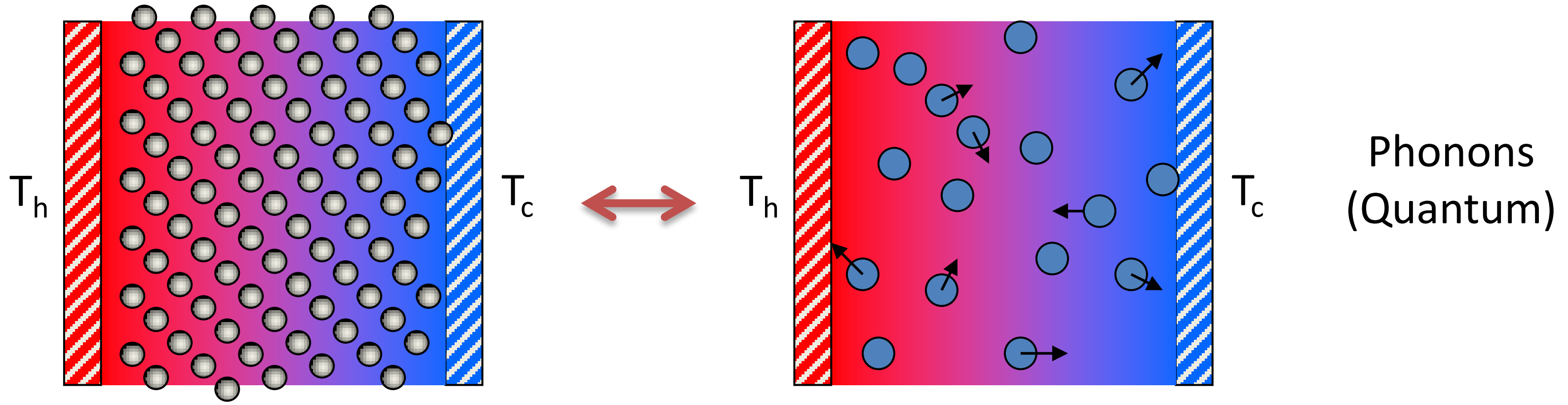
What about silicon?

k ~ 150 W/mK (300 K)

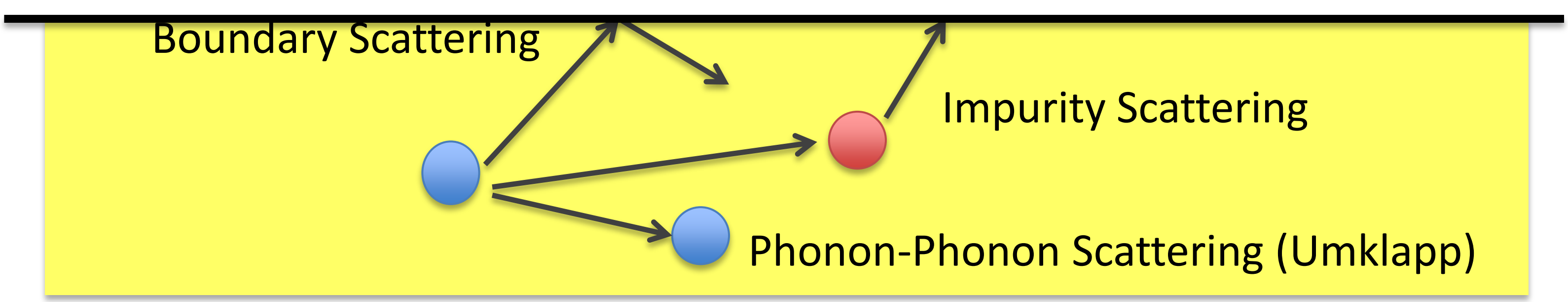
➔ *Bulk ZT ~ 0.01*

Thermal Conductivity

- Lattice vibrations conduct heat in Si



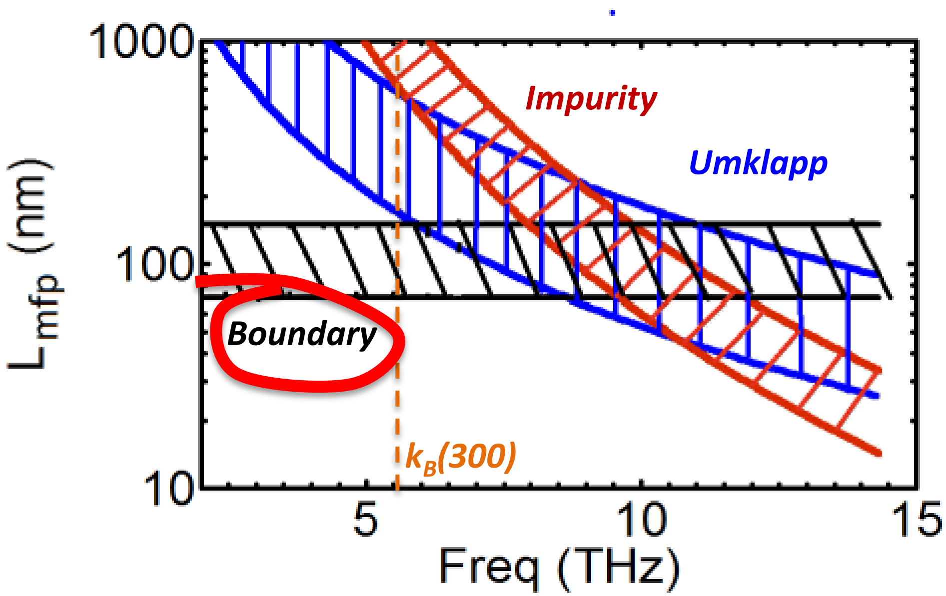
- From Kinetic theory, **k ~ C v Λ**
- Λ limited by different scattering processes

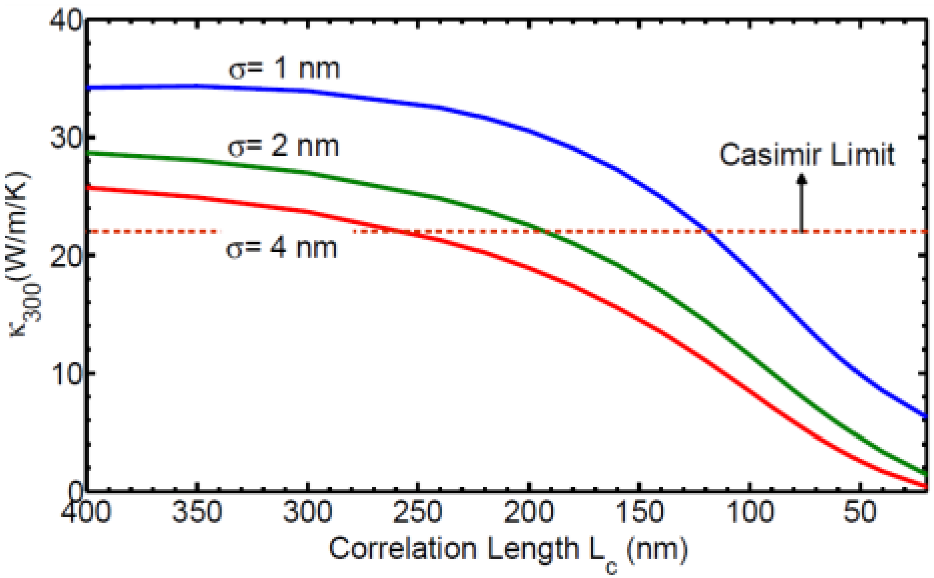


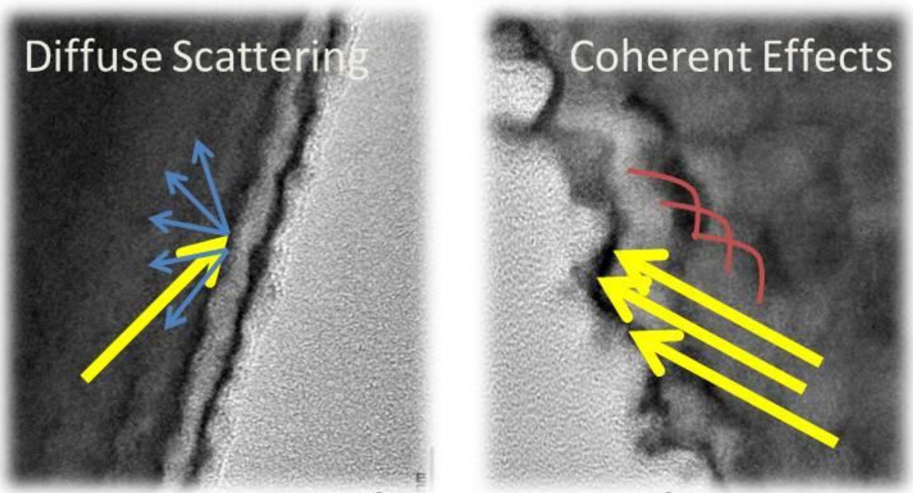
Λ_{PHONON} ~ 100-300 nm

Boundary scattering dominates *in 100 nm Si*

Phonon boundary scattering is ***frequency dependent and tunable through roughness***

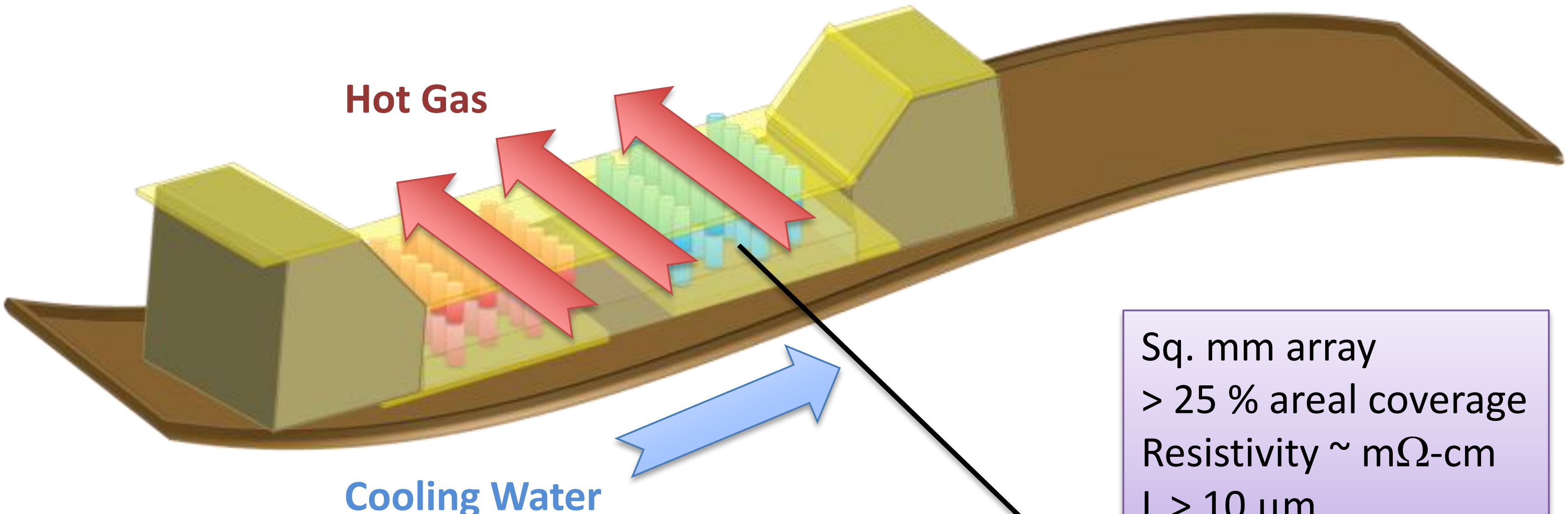






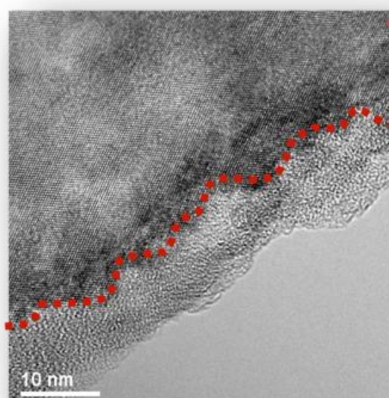
Smooth vs Rough

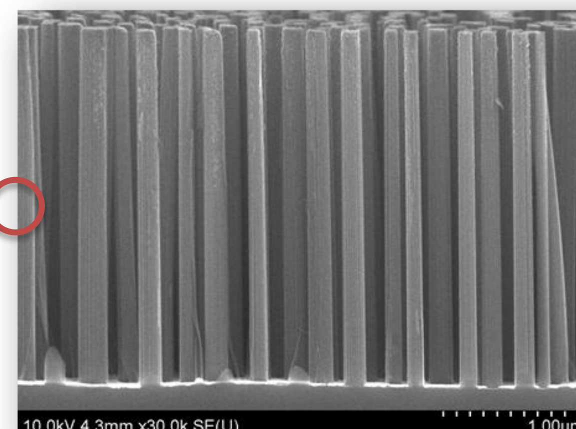
UIUC Silicon TE Device Concept



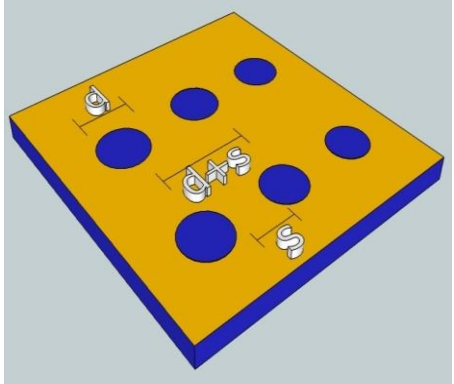
Sq. mm array
> 25 % areal coverage
Resistivity ~ mΩ-cm
L > 10 μm

Rms roughness > 2nm
Corr. Length < 100 nm
Dia < 100 nm





Wire Array Fabrication



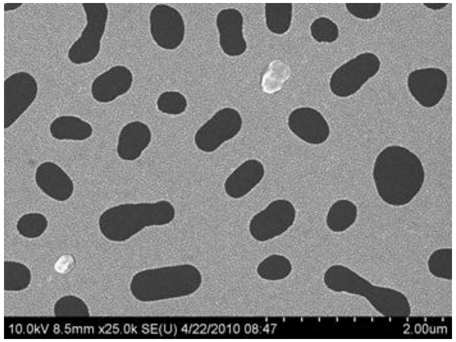
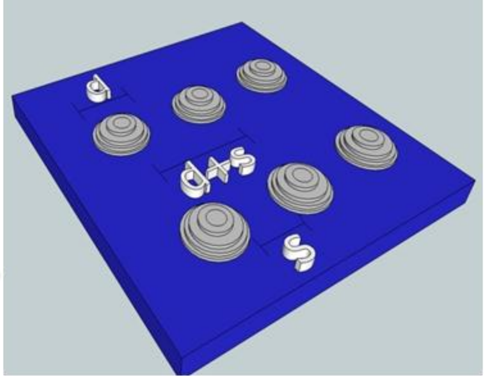
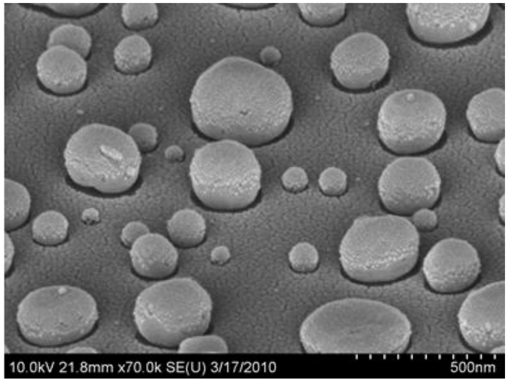
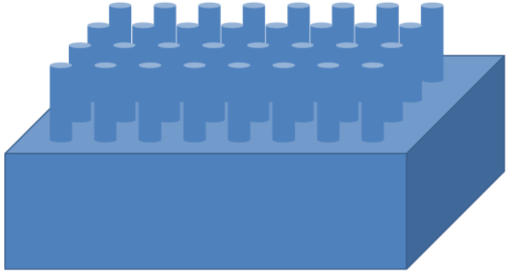


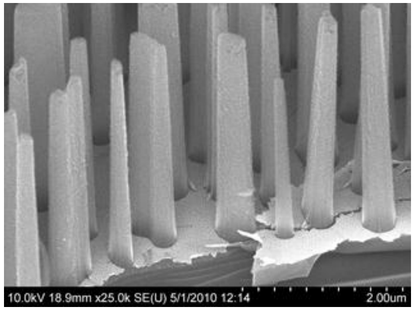
Image Reversal via Lift-Off



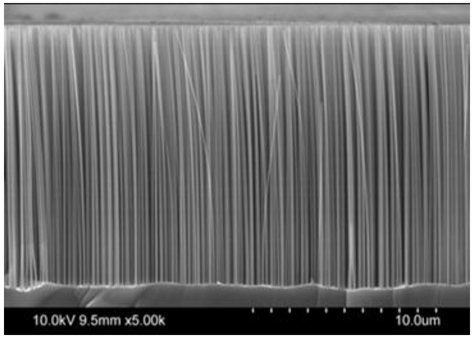


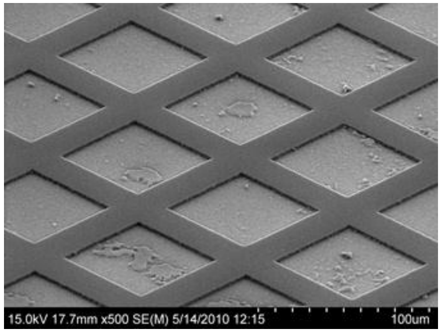
Thermal Dewetting



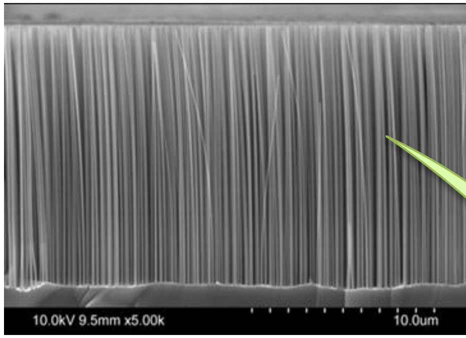


MAC-Etch

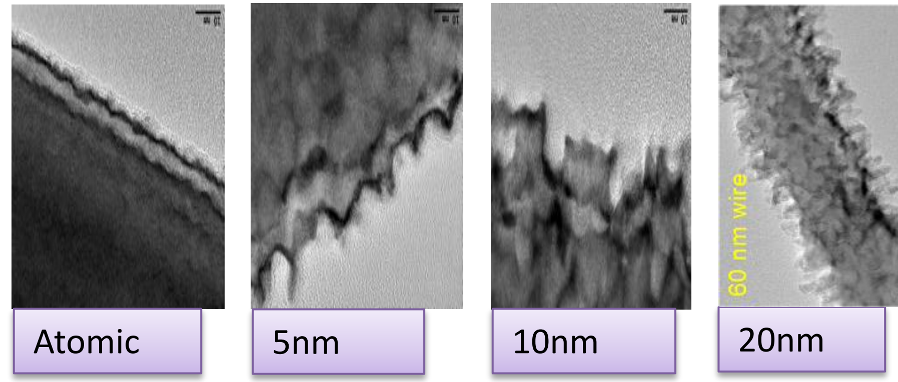


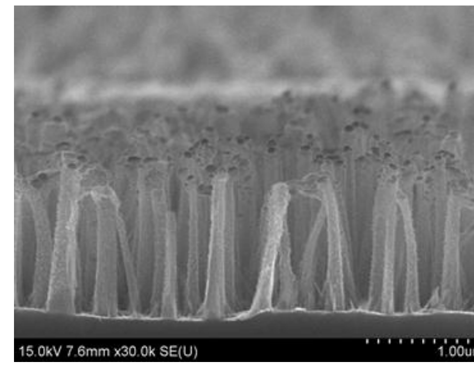


Device Formation

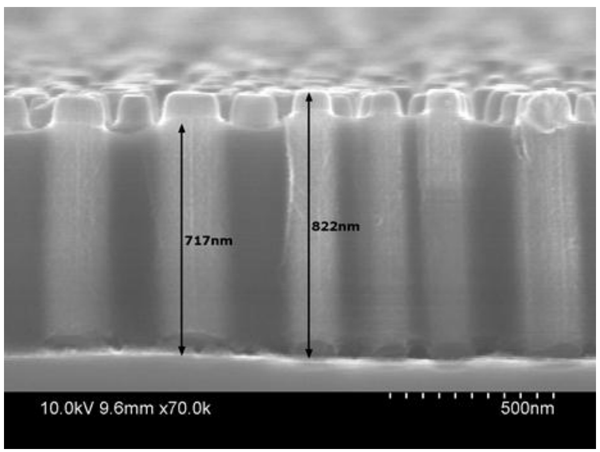


Controlled Roughness Enhancement

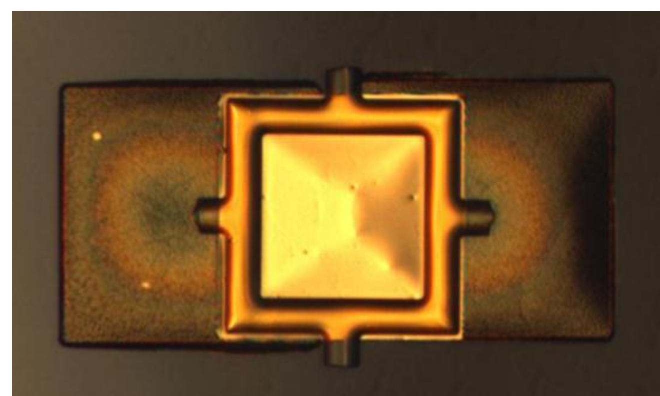




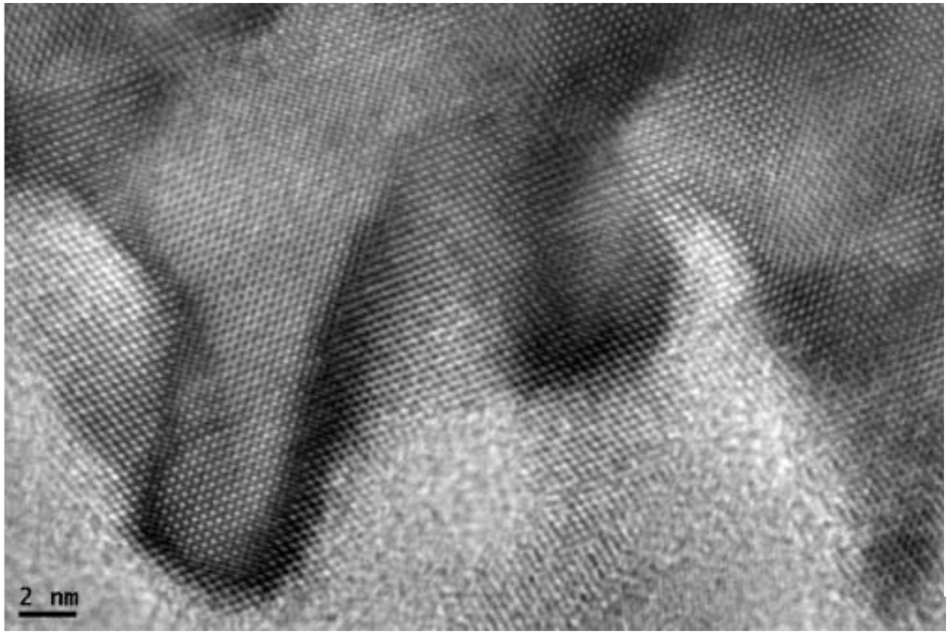
SOG/Poly Fill & Contact Formation



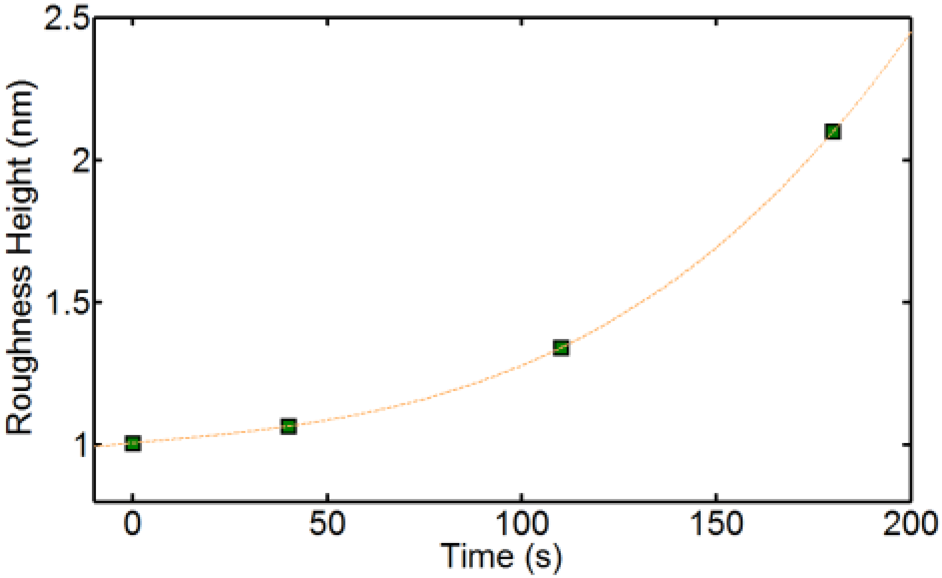
Transfer Printing (*n*- and *p*-type)



HRTEM Roughness Characterization



Roughened wire still crystalline



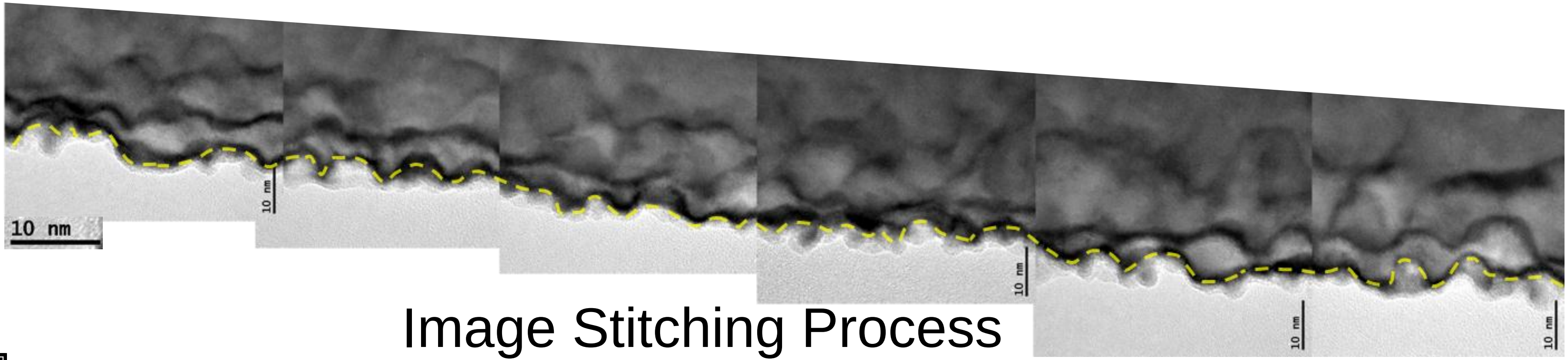
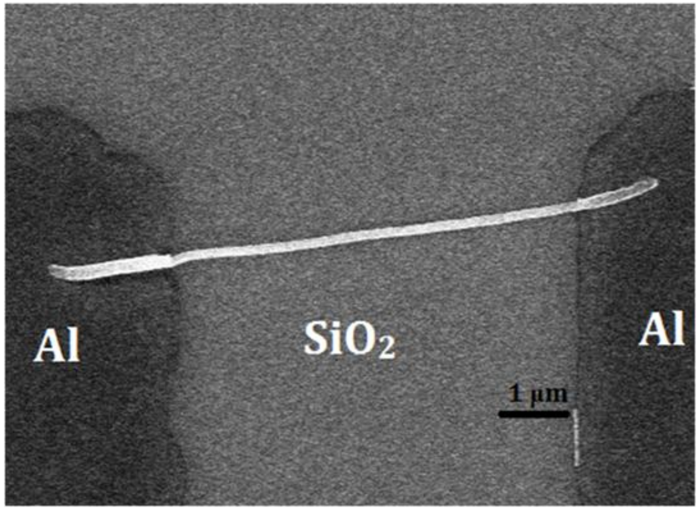
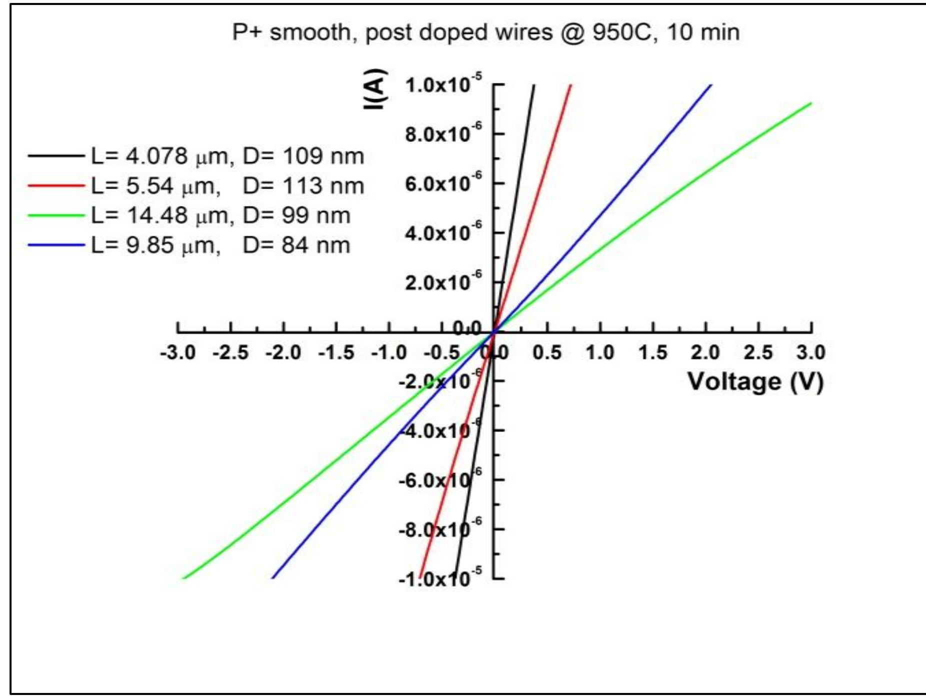
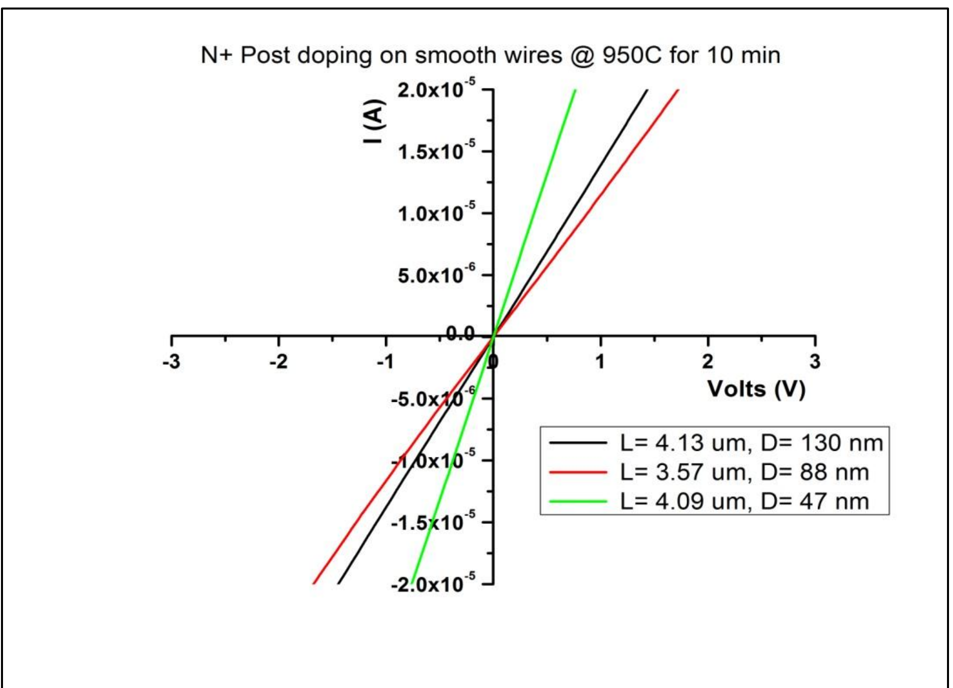


Image Stitching Process

Electrical Conductivity Measurements

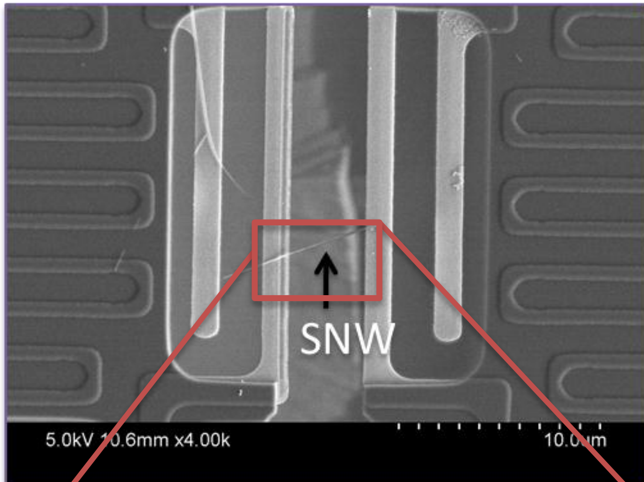


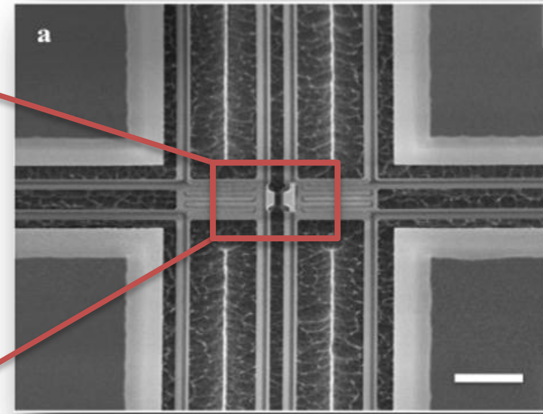


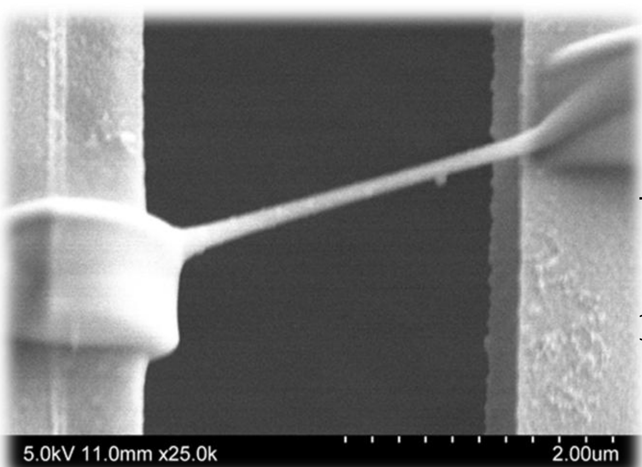


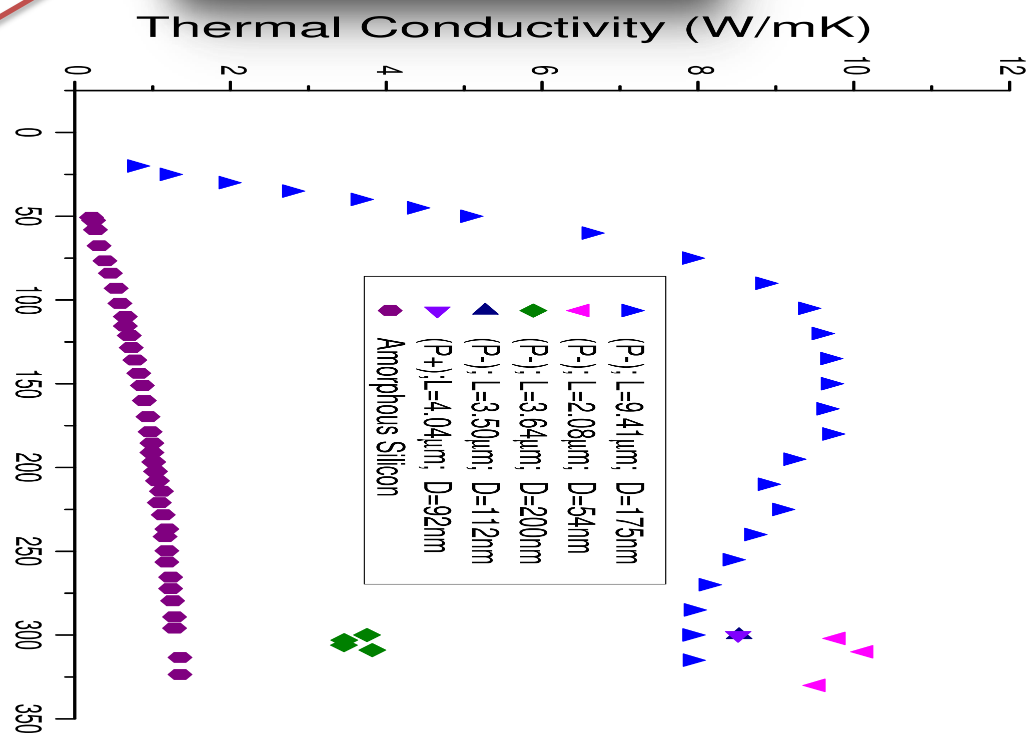
ρ can be reduced to ~1 mΩ-cm via controlled doping

Single Wire Thermal Measurements

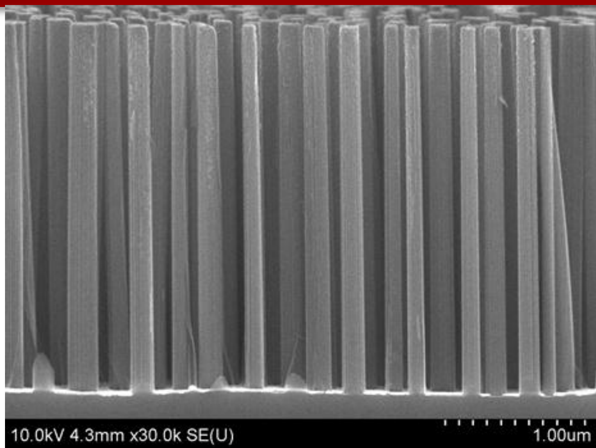


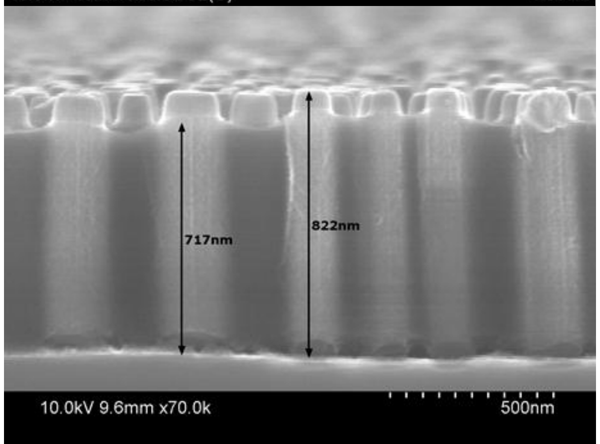


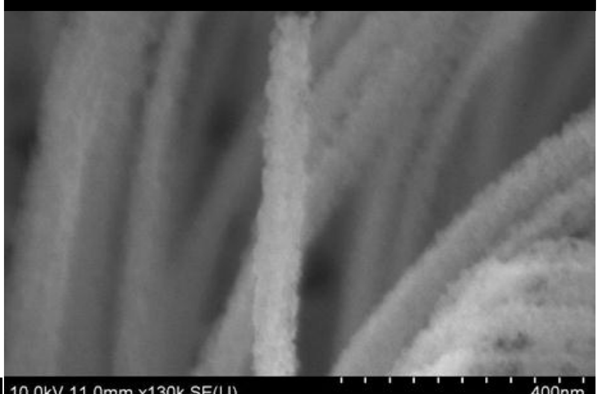


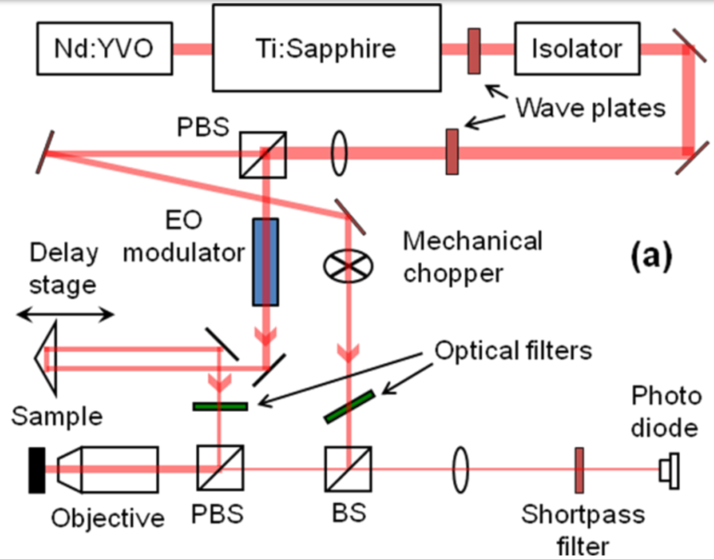


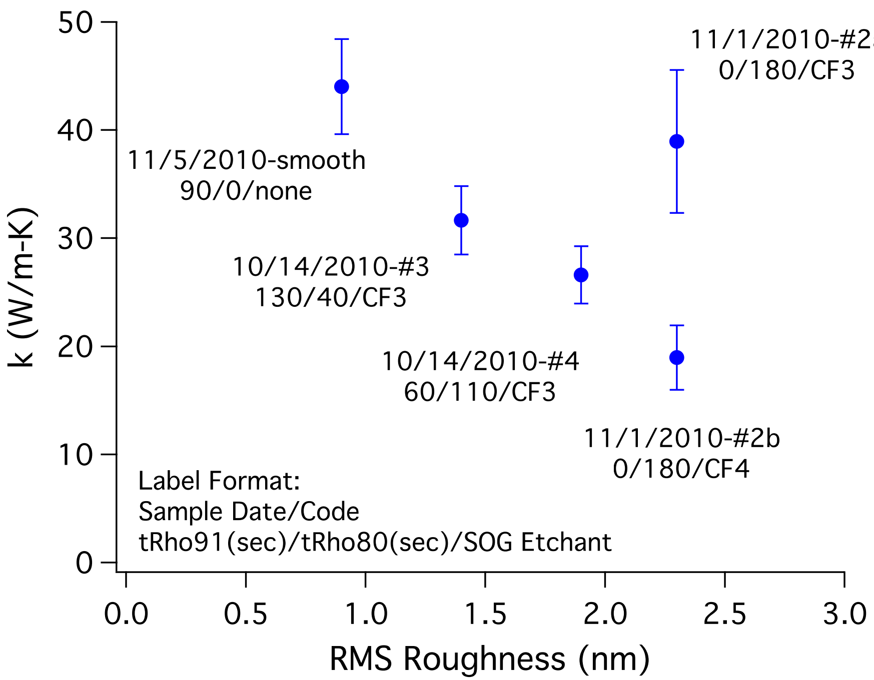
Thermal Conductivity of Wire Arrays



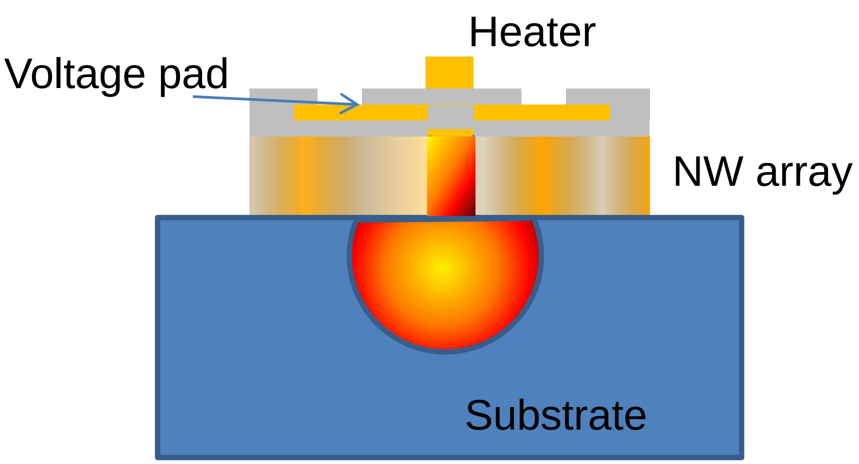


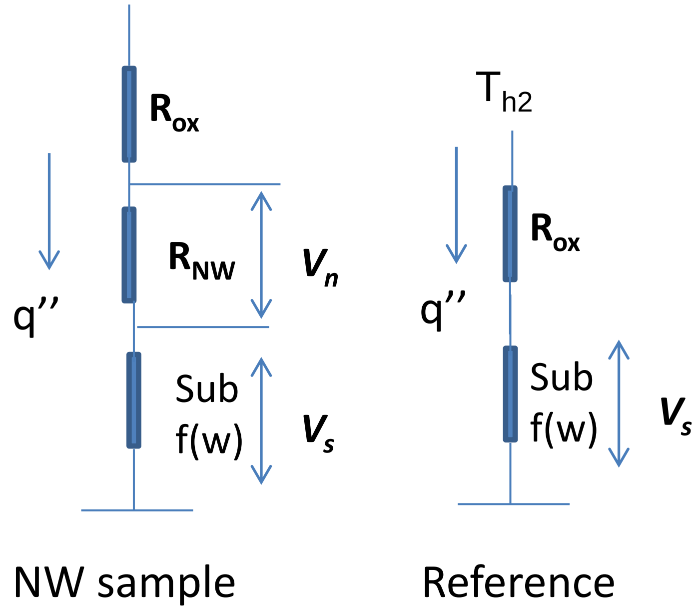


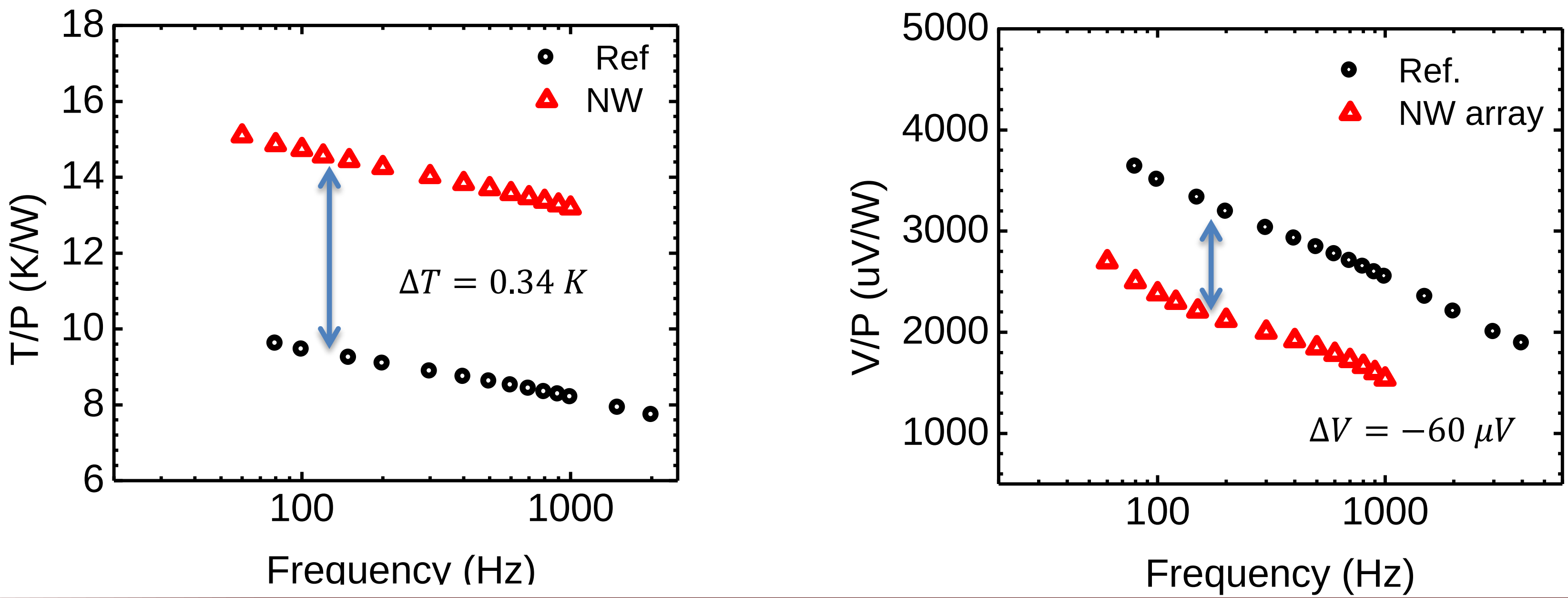




Array Seebeck and Thermal Measurements







Summary and Outlook

- Silicon thermoelectrics potentially enables unprecedented cost-effective waste heat recovery
- Ongoing work at UIUC seeks to fabricate the first truly nanostructured silicon thermoelectric device
- Preliminary characterization work shows promising trend and focus is now on device engineering


Cahill


Fang


Ferreira


Li


Rogers


Sinha


Keng


Bruno


Marc


Jun


Seok


Numair


Dongwook


Myunghoon


Krishna


Jyothi

Joe Feser   Jae Cheol   Jae Ha   Chen   Jun-Hwan